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INTEGRITY DETERMINATION OF RTK SOLUTIONS IN PRECISION FARMING APPLICATIONS

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ABSTRACT

Integrity of Real Time Kinematic (RTK) positioning solutions relates to the confidential level that can be placed in the information provided by the RTK system. It includes the ability of the RTK system to provide timely valid warnings to users when the system must not be used for the intended operation. For instance, in the controlled traffic farming (CTF) system that controls traffic separate wheel beds and root beds, RTK positioning error causes overlap and increases the amount of soil compaction. The RTK system's integrity capacity can inform users when the actual positional errors of the RTK solutions have exceeded Horizontal Protection Levels (HPL) within a certain Time-To-Alert (TTA) at a given Integrity Risk (IR). The later is defined as the probability that the system claims its normal operational status while actually being in an abnormal status, for instance, the ambiguities being incorrectly fixed and positional errors having exceeded the HPL. The paper studies the required positioning performance (RPP) of the GPS positioning system for PA applications such as a CTF system, according to literature reviews and surveys conducted among a number of farming companies. The HPL and IR are derived from these RPP parameters. A RTK-specific rover autonomous integrity monitoring (RAIM) algorithm is developed to determine the system integrity according to real time outputs, such as residual square sum (RSS), HDOP values. A two-station baseline data set is analysed to demonstrate the concept of RTK integrity and assess the RTK solution continuity, missed detection and false alarm probability.

Introduction

In recent years, precision agriculture (PA) has evolved into a hot research and commercial topic all over the world and changed the traditional farming dramatically. As defined by (NRC 1997), "Precision agriculture is a management strategy that uses information technology to bring data from multiple sources to bear on decisions associated with crop production"(Pierce & Nowak, 1999b). More specifically, PA enables real-time data collection with sufficiently accurate positioning information being used for enhancement of agricultural production such as soil sampling, tractor guidance, crop scouting, yield monitoring and variable rate applications by means of the combination of Global Positioning System (GPS) and Geographic Information System (GIS). GPS/GIS helps the customers analyse the data efficiently and make a farming plan correctly(Pierce & Nowak, 1999a). The benefits of PA include not only increasing productivity and net profit, improving water quality and wildlife habitat, saving valuable time, fuel and fertilizer, but also significantly reducing the farmers fatigue and stress by providing better decision making ability(Reid, Zhang, & Noguchi, 2000). More important, PA contributes to sustainable use of natural resources for generations to come as reducing the negative farming impacts on the environment. (Cook & Bramley, 1998) It is not difficult to understand the importance of Global Navigation Satellite Systems (GNSS) as the fundamental enabling technological element of PA. In the last two decades there have been seen a tremendous development and growth in the use of GNSS in PA, especially using Real Time Kinematic (RTK) technique. RTK is a sort of advanced differential GPS (DGPS), but using carrier phase as the measurements. RTK positioning requires a nearby, stationary reference station or network which can sent the data to the user's system, usually called the rover by a radio link. The key issue of RTK is called ambiguity resolution (AR) problem, which aims to determine the parameter of unknown carrier phase number. After the ambiguity fixed, the RTK solutions can provide centimetre accuracy which allows us applying in the application of automatic steering systems. A typical and successful case of applications is so-called Controlled Traffic Farming (CTF) in which the 2cm RMS positioning accuracy is preferred to reduce the potential for skips or overlaps and enables the farmers to seed, spray or fertilize only where they are needed—minimizing application costs and increasing productivity (see Fig. 1). Additionally, as the result of the high accuracy positioning, the CTF system can be also used to do the topography mapping whilst performing normal farming operations in the future (Tullberg, Yule, & McGarry, 2007)

Figure 1: Comparison of the Steering Results by CTF and Random traffic (Newsletter, 2009)

However, the accuracy is the simplest and most commonly used performance requirement for navigation or kinematic positioning system, but definitely not the only one. In PA, the farmers have to rely on the output of GNSS to make the decision of where to seed, water, spray and fertilize assuming it is correct. Unfortunately, the accuracy and reliability of the real time position outputs can be degraded due to various factors, such as effects of operational environment, multipath, RTCM message delays, GPS signal transmission anomaly and the system's vulnerable performance. What the worse news is that "mismanagement and a lack of investment means that some of the crucial GPS satellites could begin to fail as early as next year (2010)" according to the report of the US government accountability office (GAO) (Bobbie Johnson, 2009). That could mean that some unreliable GPS satellites would have to keep operating. Therefore, we need more than ever to devise a technique to detect any possible failures and warn the user using the potentially misleading navigation information. This is so-called integrity requirement, a measure of the trust which can be placed in the correctness of the information supplied by the total system, as defined as in the International Civil Aviation Organization (ICAO) (S. Feng & Ochieng, 2007a). Integrity includes the ability of a system to provide timely and valid warnings to users, know as alerts, when the system must not be used for the intended operation. One of the most efficient and popular tool to address this problem is Receiver Autonomous Integrity Monitoring (RAIM) technique as described in (Brown, 1988; Y. C. Lee, 1986;Feng *et a*l 2009; Hewitson & Wang, 2006; Todd Walter, 2003) This rest of the paper is organized as follows. Section 2 investigates the status of RTK application in PA and the different accuracy requirement, also gives the corresponding CTF integrity requirement. Section 3 briefly describes the method of snapshot RAIM, including the test statistic and calculation of the Horizontal Protection Level (HPL). In Section 4, the experimental studies are performed based on real GPS baseline to demonstrate the results of different situation. Finally the conclusions are presented in Section 5.

The Status of RTK Application in Precision Agriculture

The components of PA include: GPS; GIS; Grid sampling; Variable rate technology; Yield monitors; Yield mapping; Remote sensors; Auto-guidance; Proximate sensors and Computer hardware and software(Srinivasan, 2006). As the fundamental element of PA technology, GNSS plays a pivotal role for agricultural vehicle guidance such as CTF. Generally, we can evaluate the performance of CTF system in terms of the four required positioning performance (RPP) parameters: accuracy, integrity, continuity and availability. The more details about the four parameters can be referred to the literatures regarding GPS aviation navigation, such as (Brown, 1996; S. Feng & Ochieng, 2007b; Ober, 2003; Rtca, 2001; Sturza,

1988) As far as the RTK accuracy and integrity performance characteristics are concerned, this paper refers to (Y. Feng & Wang, 2008)for definition.

The Accuracy Requirement for PA

It is not wrong to pursue the highest level of accuracy for the sake of academic and scientific causes. However, this pursuit does not apply in the commercial are, where the higher the accuracy, the higher the cost. For instance, it is not wise to buy a $3,000 sub-meter DGPS receiver for personal route guidance applications if the same function can be achieved with only a $99 GPS. The important thing is to make correct decision based on the accuracy requirements of diverse farming operations.

According to surveys and literature reviews some researchers classify farming operations in to rough (soil sampling, weed scouting), fine (pesticide application, soil cultivation), and precise (planting, plowing) navigation categories and give the conservative requirements for each of the navigation categories as 1m, 10cm and 1cm (Auernhammer & Muhr, 1991; McLellan & Friesen, 1996; Nieminen, Mononen, & Sampo, 1994). Table 1 gives a summary of various positioning techniques/services, costs and accuracy requirements and their suitability for different agriculture applications.

Table 1 GPS Positioning Methods Versus PA Accuracy Requirements

Positioning Method	Option	Cost	Uses in Agriculture
Standard Positioning	Meters	$80-300	Rough positioning, Scouting (50-100m)
WAAS/EGNOS, Beacon, OmniSTAR VBS	Sub-meter	$1k-4k	Yield mapping(2-5m), Pre-tilling (1-2m)
OmniSTAR XP/HP, Local DGPS	Decimetre	$5k-10k	Automated machine guidance (10-20cm), Yield mapping(0.5-2m), GIS surveys (0.5-2m), Soil sampling (horizontal:5-10cm; vertical:5-50 cm),
RTK, Network RTK	Centimetre	>$25k	Automatic steering (2cm); Planting (5cm); Spraying-twice (5cm); Cultivation- twice(5cm); Harvesting (5cm); Seeding (2-20cm);

Although a CTF system is a very expensive positioning system, it has the highest level of accuracy (2 to 5 cm) which can bring many benefits to customers (Yule, 1998). The problem is that no RTK system can be guaranteed to provide such level of accuracy at all times. In this case, the users need to know whether the system work properly, otherwise some safety or unexpected liability issues will occur. Due to these problems, the need for an effective method for monitoring GPS integrity is required.

The Integrity Requirement for PA

Integrity requirements for positioning in PA are twofold: machinery safety and PA operation liability. It is reported that machinery related accidents to account for 10 percent of 200,000 farm accidents in 1993 in the USA with a couple of injuries being fatal(Murphy & Morrow, 1996).Hence, to avoid injuries and to warrant machine function, operation performance and the prevention of accidents, adequate safety has been a demand for autonomous agricultural vehicles(Jahns, 1975). Taking into account the physical necessity of proximity between harvester and truck, for example, unreliable auto-guided harvester would involve a prohibitive potential risk of accident if it loses control and rushes against the truck. Therefore, auto-guided systems must always behave safely and a serious means of evaluating their performance is highly recommended. The liability refers to the level of cost, due to inappropriate operation, and the side-effect, such as to environment.

In these applications, it is essential that farmers be assured that a system is operating within design tolerances and that the position estimates derive from it can be trusted to be within specifications. System

Integrity is the ability of the system to provide timely warnings to users when it should not be used for operation. To specify the integrity concept, there are three parameters involved: horizontal alert limit (HAL), time-to-alert (TTA), and integrity risk (IR) (S. Feng & Ochieng, 2007a). More specifically, HAL is the maximum horizontal position error allowable for a given navigation/positioning mode (e.g., en route, nonprecision approach) without an alert; TTA is the maximum allowable elapsed time from the onset of a positioning failure until the equipment annunciate the alert (Kalafus & Chin, 1988). IR is the probability that the navigation positioning error exceeds the alert limit and the event is not detected (Y. Lee, Van Dyke, DeCleene, Studenny, & Beckmann, 1996).

Based on the required navigation parameter (RNP) given by ICAO, we can extend the concepts into the PA applications. The accuracy requirement is 2- dimensional horizontal RMS circle around the true position; in other words it means the position error is within the accuracy requirement should be 95% of time. The alert limit for integrity is the positioning accuracy of 99.7% which is probably about 3 times of the accuracy specification. In terms of other parameters, the mediate reference values are adopted in this paper (S. Feng & Ochieng, 2007a). Table 2 gives an example of the RPP for precision agriculture.

Table 2. Example RPP for Precision Agriculture

Mode of Manipulation	Horizontal Accuracy	Integrity			Continuity	Availability
		Horizontal Alert Limit	Integrity Risk	Time to Alert		
Yield mapping	1m	2.5m	10^{-6}/h	15 sec	10-5/h	0.997
Automated machine guidance	20cm	0.5m	10^{-6}/h	10 sec	10-5/h	0.997
Spraying twice	5cm	0.15m	10^{-6}/h	5 sec	10-5/h	0.997
CTF	2cm	6cm	10^{-6}/h	5 sec	10-5/h	0.997

Modified snapshot RAIM method in RTK positioning

The idea of the receiver autonomous integrity monitoring (RAIM) as firstly proposed by (Grover Brown, 1992)was detects faults with redundant GPS pseudorange measurements. That is, when more satellites are available than needed to produce a position fix, the extra pseudoranges should all be consistent with the computed position. A pseudorange that differs significantly from the expected value may indicate a fault of the associated satellite or another signal integrity problem. The test statistic used is a function of the pseudorange measurement residual (the difference between the expected measurement and the observed measurement) and the amount of redundancy. The test statistic is compared with a threshold value, which is determined based on the requirements for the probability of false alarm (P_{FA}) and the probability of missed detection (P_{MD}).

In the RTK positioning, the double differenced (DD) pseudorange and carrier phase measurements are used instead of un-differenced pseudorange measurements, involving ambiguity resolution (AR) and position estimation, thus the RAIM problem become more complicated. The existing RAIM algorithms detect DD phase outliers in snapshot solutions or filtering solutions, such as in (S. Feng & Ochieng, 2006; Hewitson & Wang, 2007; Kovach, Maquet, & Davis, 1995). In the following, the prior ambiguity solutions are used along with the current measurements, referring to Chang (Chang *et a*l, 2001), where the model was called the double difference prior information model. From integrity determination perspective, it is a modified snapshot method, but considering the previous ambiguity solutions.

Basic Equations

With two dual-frequency GPS receivers, one can form two double differenced (DD) carrier phase and code observation equations, respectively:

$$\Delta\phi_1 = \Delta\rho + -\frac{\Delta I}{f_1^2} - \lambda_1 \Delta N_1 + \varepsilon_{\Delta\phi 1} \tag{1}$$

$$\Delta\phi_2 = \Delta\rho - \frac{\Delta I}{f_2^2} - \lambda_2 \Delta N_2 + \varepsilon_{\Delta\phi 2} \tag{2}$$

$$\Delta P_1 = \Delta\rho + \frac{\Delta I}{f_1^2} + \varepsilon_{\Delta P1} \tag{3}$$

$$\Delta P_2 = \Delta\rho + \frac{\Delta I}{f_2^2} + \varepsilon_{\Delta P2} \tag{4}$$

In (1) to (4), the symbol "Δ" represents double difference operations between satellites and receivers; $\Delta\phi_1$,and $\Delta\phi_2$ are phase signals on L1 and L2 frequencies, ΔP1 and ΔP2 are code measurements on L1 and L2 carriers; the symbol Δρ is the geometric distance between satellite and receiver antenna; $\frac{\Delta I}{f_1^2}$ and $\frac{\Delta I}{f_2^2}$ are the ionospheric propagation errors with respect to L1 and L2 carriers respectively.For a two-receivers baseline, one can form the geometry-based observational equations directly for the $\Delta\phi_1$,and $\Delta\phi_2$ observables.

Feng (2008) suggested use of the optimally combined virtual phase code measurements instead of original signals for more efficient geometry-based AR, based on the minimal total noise level in cycles, which actually reduce the correlation between selected combined DD measurements. For instance, the combined code observable is less noisy over a medium baseline over which the magnitude of code noise may be larger than the effect of ionosphere:

$$\Delta P_{12} = \frac{f_1 \Delta P_1 + f_2 \Delta P_2}{f_1 + f_2} \tag{5}$$

One can use the widelane phase measurement

$$\Delta\phi_{12} = \frac{\cdot f_1 \cdot \Delta\phi_1 - f_2 \cdot \Delta\phi_2}{f_1 - \cdot f_2} \tag{6}$$

along with the narrowlane phase measurement

$$\Delta\phi_{43} = \frac{4 f_1 \Delta\phi_1 - 3 f_2 \Delta\phi_2}{4 f_1 - 3 f_2} \tag{7}$$

to form the 3p observation equations for each-receivers viewing p+1 satellites:

$$\begin{bmatrix} \Delta \mathrm{P}_{12} - \Delta\rho_0 \\ \Delta\phi_{12} - \Delta\rho_0 \\ \Delta\phi_{43} - \Delta\rho_0 \end{bmatrix} = \begin{bmatrix} A_1 & 0 & 0 \\ A_1 & -\lambda_{12} I & \lambda_{12} I \\ A_1 & -4\lambda_{43} I & 3\lambda_{43} I \end{bmatrix} \begin{bmatrix} \delta X \\ \Delta N_1 \\ \Delta N_2 \end{bmatrix} + \begin{bmatrix} \varepsilon_{\Delta \mathrm{P}12} \\ \varepsilon_{\Delta\phi 12} \\ \varepsilon_{\Delta\phi 43} \end{bmatrix} \tag{8}$$

where A1 is the p-by-3 design matrix for the user coordinates vector δX, I is the p-by-p identical matrix; and the effects of ionospheric and tropospheric biases were eliminated in the model over short-baselines. Direct detection of faulty DD phase measurements is difficult due to the redundancy of the equation system as low as (p-3). However, we can always assume that the ambiguity parameters in the previous epoch has been resolved, and the fixed integers can be used as an prior "measurements" of the ambiguity parameters of the current epoch, that is, we have the additional observation equations (Chang et al., 2001)

$$\begin{bmatrix} \Delta N_1 \\ \Delta N_2 \end{bmatrix}_{k-1} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} \Delta N_1 \\ \Delta N_2 \end{bmatrix}_k + \begin{bmatrix} \varepsilon_{\Delta N1} \\ \varepsilon_{\Delta N2} \end{bmatrix}_{k-1} \tag{9}$$

where k and k-1 represent the current and previous data epoch; Let

$$L=\begin{bmatrix}\Delta P_{12}-\Delta\rho_0\\ \Delta\phi_{12}-\Delta\rho_0\\ \Delta\phi_{43}-\Delta\rho_0\\ (\Delta N_1)_{k-1}\\ (\Delta N_2)_{k-1}\end{bmatrix}\quad H=\begin{bmatrix}A\\A\\A\\0\\0\end{bmatrix}\quad B=\begin{bmatrix}0&0\\-\lambda_{12}I&0\\0&-\lambda_{43}I\\I&0\\0&I\end{bmatrix},$$
$$\Delta N=\begin{bmatrix}\Delta N_1\\ \Delta N_2\end{bmatrix}\quad e=\begin{bmatrix}\varepsilon_{\Delta P12}\\ \varepsilon_{\Delta\phi 12}\\ \varepsilon_{\Delta\phi 43}\\ \varepsilon_{\Delta N1}\\ \varepsilon_{\Delta N2}\end{bmatrix} \tag{10}$$

the general formation of geometry-based linear observational equations is expressed as follows

$$\mathrm{L=H\delta X+B\Delta N+e} \tag{11}$$

$$E(e)=0,\; Cov(e)=\sigma_0^2P^{-1}=\sigma_0^2\begin{bmatrix}Q_{\Delta P12}&0&0\\0&Q_{\Delta\phi}&0\\0&0&Q_{(\Delta\hat{N})k-1}\end{bmatrix} \tag{12}$$

where:

σ_0^2 is the unit-weight variance parameter.

P-1 is the 5p-by-5p weight matrix giving the relative importance between all the observations.

$\sigma_0^2 Q_{\Delta P12}$ is the p-by-p covariance matrix for the DD ΔP_{12} code measurements.

$\sigma_0^2 Q_{\Delta\phi}$ is the 2p-by-2p covariance matrix given for the DD phase $\Delta\phi_{12}$ and $\Delta\phi_{43}$ phase measurements.

$\sigma_0^2 Q_{(\Delta N)k-1}$ is the 2p-by-2p covariance matrix of the ambiguity vector obtained in the (k-1) th epoch.

Test Statistic and Threshold

After we get the floating solutions from equation (11) and (12), LAMBDA method is adopted to get the integer ambiguity, and then use the integer ambiguity to improve the floating solutions. A standard procedure can be found in (de Jonge, Tiberius, & Teunissen, 1996; Teunissen, De Jonge, & Tiberius, 1997). When we get the integer ambiguity of $\Delta\phi_{12}$ and $\Delta\phi_{43}$, either of them can be used to estimate the position because our interest is not the accuracy but the ability of integrity monitoring. In this paper, $\Delta\phi_{43}$ is used as the inputs of measurement y. The corresponding residual vector is

$$v=y-\hat{y}=[I-G(G^TPG)^{-1}G^TP]y \tag{13}$$

The sum of squares of weighted residuals (SSWR) is then obtained

$$\mathrm{SSWR}=v^TPv \tag{14}$$

if the observation noise vector is normal distribution,

$$e\sim N(0,\sigma_0^2P^{-1}) \tag{15}$$

In the absence of any measurement fault, the RSS residuals follow a central chi-square distribution χ_α^2 of (p-3) degrees of freedom, that is,

$$\frac{v^TPv}{\sigma_0^2}\sim\chi_\alpha^2(p-3) \tag{16}$$

where p is the total number of $\Delta\phi_{43}$ measurements.

After that we can apply the following criterion to detect whether the system works properly based on hypothesis testing. As SSWR is constructed to be test statistic and the corresponding detection threshold variable is T, then H_0 is the null hypothesis (no fault) and H_1 is the alternative hypothesis (with fault satellites). Therefore, we have

$$\begin{aligned} H_0 &: \quad SSWR < T \\ H_1 &: \quad SSWR \geq T \end{aligned} \tag{17}$$

Thus if SSWR less than T, it is normal state; otherwise the fault is detected. The performance of this test can be characterized by P_{FA} and P_{MD} (Mark A. Sturza, 1988):

$$\begin{aligned} P_{FA} &= [SSWR \geq T \mid H_0] \\ P_{MD} &= [SSWR < T \mid H_1] \end{aligned} \tag{18}$$

Horizontal Protection Level

In addition to detection of the faults in the DD phase measurements through chi-square testing, the RAIM algorithm also includes determination of the horizontal protection level (HPL), which is an upper bound that a horizontal position error must not exceed with a given PFA and PMD. HPL is defined as a function of the visible satellites, user geometry, and expected error characteristics. Given the horizontal dilution of precision (HDOP)

$$HDOP = \frac{\sqrt{\sigma_E^2 + \sigma_N^2}}{\sigma} \tag{19}$$

The HPL is given by

$$HPL = k_H \cdot \sigma_H = k_H \cdot \sigma \cdot HDOP \tag{20}$$

where k_H is the factor that reflect the probability of missed detection.

There are four conditions which can happen as shown in Table 3 (Kalafus & Chin, 1988). In the next section, different experiment scenarios are carried out to obtain the real statistic information about the false alert and missed detection conditions.

Table 3 Integrity Conditions

		Test Statistic Exceeds Alarm Threshold?	
		NO	YES
Position Error Exceeds Protection Level	NO	Normal Operation	False Alert
	YES	Missed Detection	Detection

The above process limits to traditional RAIM concept, which is called Fault Detection (FD) only. The goal of fault detection is to detect the presence of a positioning failure. An enhanced version of RAIM employed in some receivers or system is known as Fault Detection and Exclusion (FDE). It uses a minimum of 6 satellites to not only detect a possible faulty satellite, but to exclude it from the navigation solution so the navigation function can continue without interruptions. FDE in RTK solutions is also possible, and the procedure is:

Computer the residual parameter as test statistic using all the satellites from equation (14).If test statistic is less than the threshold, assume there is no fault, otherwise give a failure detection alarm. If a failure detected, repeat step (1) and (2) with deleting a satellite one by one. Once the subset test statistic is less than the threshold, the satellite deleted is flagged as the fault satellite and not be used in the next process(Parkinson & Axelrad, 1988).

Experimental Analysis

The purpose of the experimental analysis is to verify the performance of the model and RAIM detection algorithm against the different levels of single failures on the L1 phase DD measurements.
Generally, there are two types of failure as outlined by RTCA SC-159 GPS Integrity Working Group: slow ramp, e.g., satellite oscillator failure resulting in a slow code and carrier phase drift and step error, e.g., bad ephemeris upload, cycle slips.

The numerical experiment examine several computation scenarios, to demonstrate delectability of the proposed algorithm for the above two types of measurement faults, based on processing a real baseline data set. Table 4 gives the data set used in the experimental studies and observation weight settings in the model, as well as the computation scenarios and the probability of false alert.

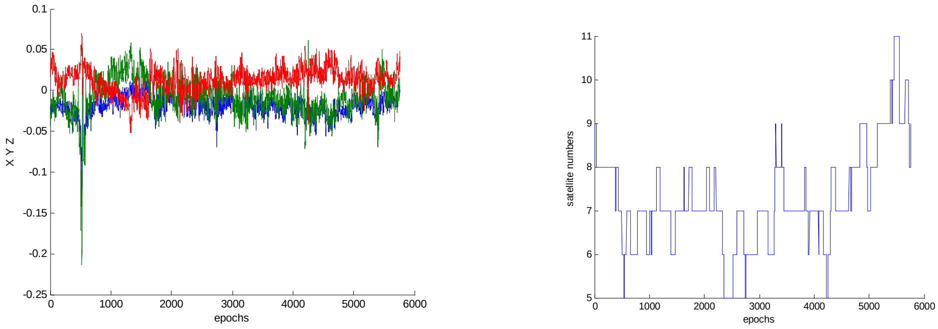
Table 4 Description of data sets and settings in geometry-based models

Data information	
Data source/Date	www.cors.ngs.gov, 1 Jan 2007
Data sets/format	P474 and P478, RINEX
Data length/total epochs	24 h, 5760 epochs
Sample rates	15 seconds
Baseline	21 km
Cut-off angle	15 degrees
Settings in the models (10) and (11)	
A priori variances for Δφ12 and Δφ43	(0.028m)2, (0.014m)2
A priori variance for P12	(0.425m)2
Computation Scenarios	
(I) No additional errors added to any measurements	
(II) 0.25 cycle drift error added to one of the rover L1 carrier phases	
(III)0.5 cycle drift error added to one of the rover L1 carrier phases	
(IV) 1 cycle drift error added to one of the rover L1 carrier phases	
(V) 2.5 cycle drift error added to one of the rover L1 carrier phases	
(VI) A ramp error at 0.1m/epoch rate added to one of the rover L1 carrier phase	
(VII) A ramp error at 0.01m/epoch rate added to one of the rover L1 carrier phase	
(VIII) Remove the measurement to which the error was added in (I)-(VII)	
Probability of false alert= 3.33×10-7/sample Probability of missed detection= 0.001	

Note: the error was added only to non-reference satellite.

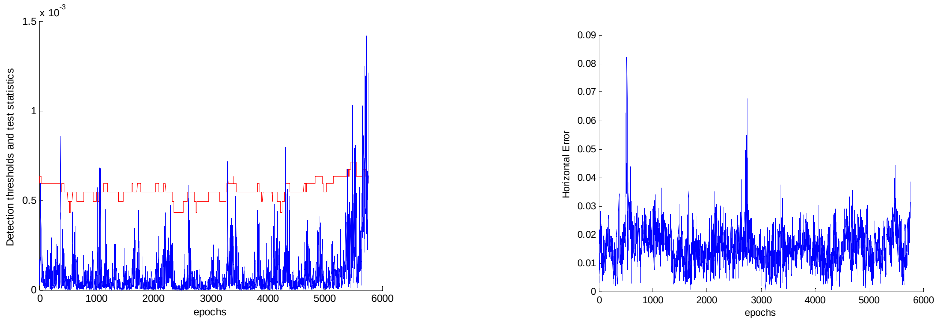
Figure 2 shows the position errors (a) and the visible satellite numbers (b) under the computation Scenario I, in which the all ambiguities were correctly resolved and fixed to integers. The large positioning error around the epoch 533 was due to poor geometry formed by only five visible satellites. Figure 3 plots the threshold line against the test statistics (a) and the corresponding horizontal errors in (b). The test statistics larger than the threshold indicates the presence of false alerts, 56 out of the total of 5760 epochs. It also can be found that the horizontal errors become larger when there are only five satellites at least two epochs. Figures 4, 5, 6 and 7 show that the test statistics plotted against the detection thresholds for the computation Scenario II, III, IV and V respectively. The numbers of missed detections in these four scenarios are 41, 22, 0 and 0 respectively. Not surprisingly, the larger the added drift errors, the more powerful of the detection function. In other words, large errors can detected more effectively due to their large influence on the test statistic.

Figure 8 and Figure 9 show that the test statistics plotted against the thresholds with the ramp error at a rate 0.01m/epoch and 0.1m/epoch respectively. The number of missed detection condition is 165 and 3 respectively. The figure of 'field sawtooth' is because when the reference satellite changes, the ramp error start over again. It is easy to see that the bigger ramp errors are more detectable. Figure 10 shows the horizontal protection level which can reflect the real horizontal error at most epochs with the probability of missed detection 0.001. Figure 11 (a) shows the position error after removing the fault satellite, the abnormal large error occurring on two places is due to the wrong ambiguity solution with rare satellite number; (b) shows the detection threshold and test statistics, the blank is due to the no redundancy. Table 5 summarizes the overall probability of false alert and missed detection from these experiments. Specifically, the probability of false alert is obtained from the normal operation scenario while the probabilities of missed detection are obtained from other six scenarios with different magnitude added errors.



a b

Figure 2. Illustration of position errors without any simulation errors (all the ambiguity integers are correct), and the visible satellite numbers



a b

Figure 3. Illustration of detection thresholds and test statistics, and the horizontal errors in the case of no simulation errors

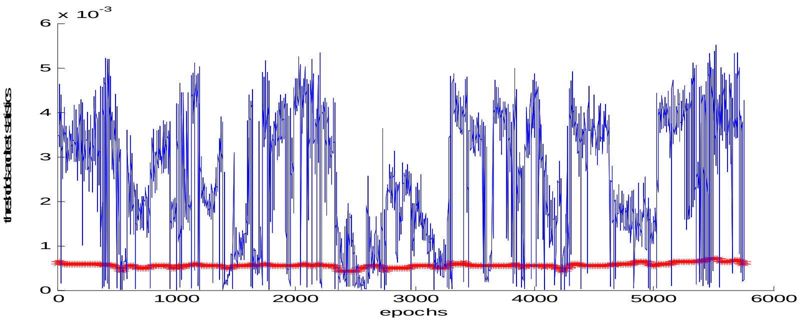


Figure 4. Illustration of detection thresholds and test statistics in the case where a 0.25 cycle drift error was added to one of the rover L1 carrier phases

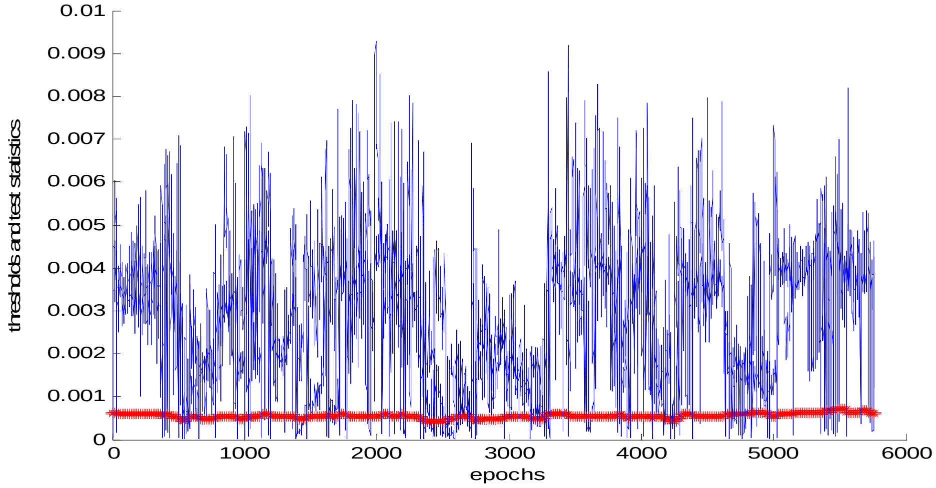


Figure 5. Illustration of detection thresholds and test statistics in the case where a 0.5 cycle drift error was added to one of the rover L1 carrier phases

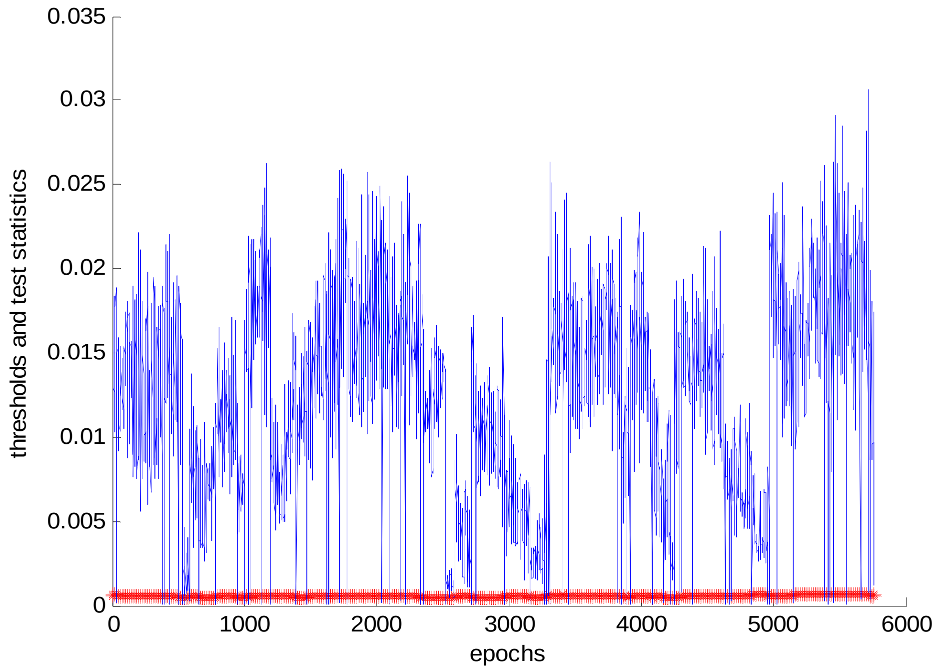


Figure 6. Illustration of detection thresholds and test statistics in the case where a 1 cycle drift error was added to one of the rover L1 carrier phases

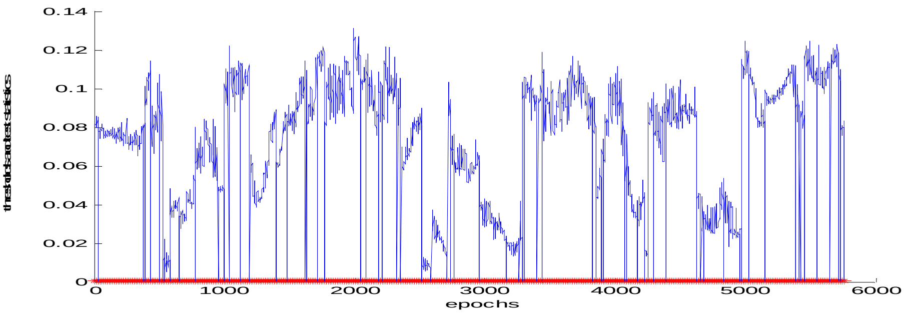


Figure 7. Illustration of detection thresholds and test statistics in the case where a 2.5 cycle drift error was added to one of the rover L1 carrier phases

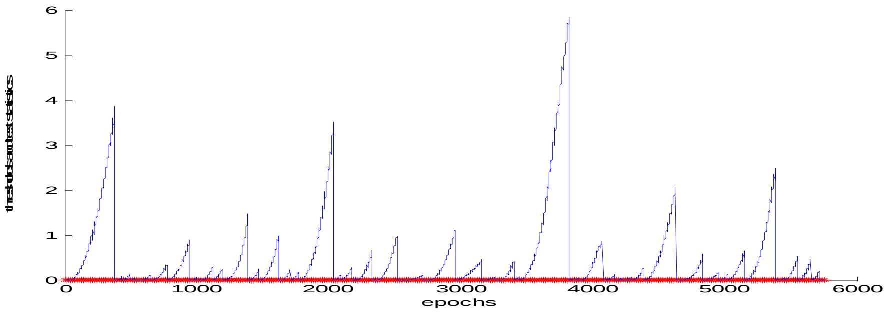


Figure 8. Illustration of detection thresholds and test statistics in the case of ramp error at the 0.01m/epoch rate added to one of the rover L1 carrier phase

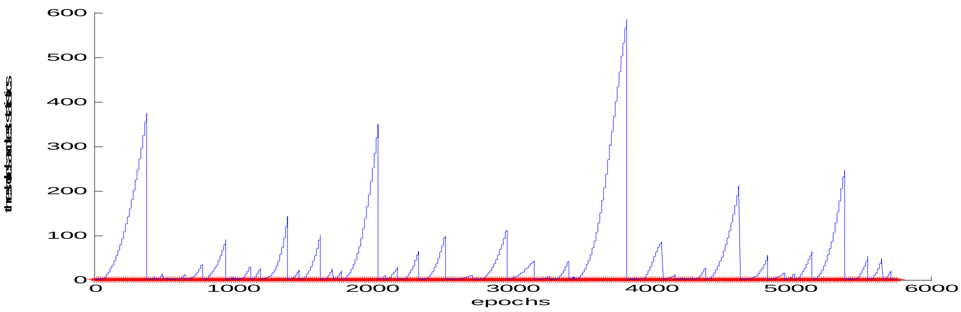


Figure 9. Illustration of detection thresholds and test statistics in the case of ramp error at the 0.1m/epoch rate added to one of the rover L1 carrier phase

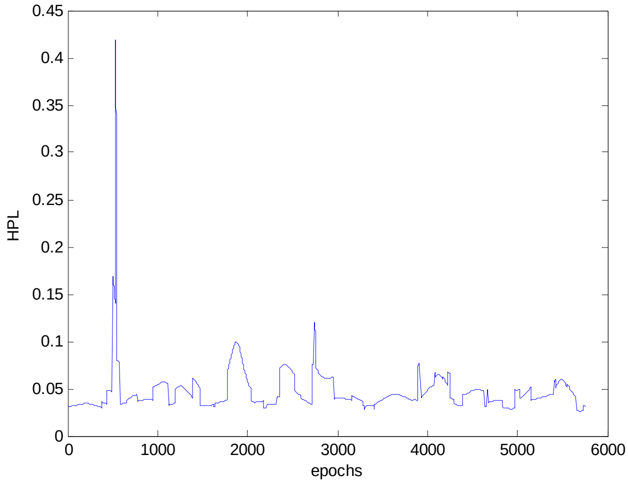
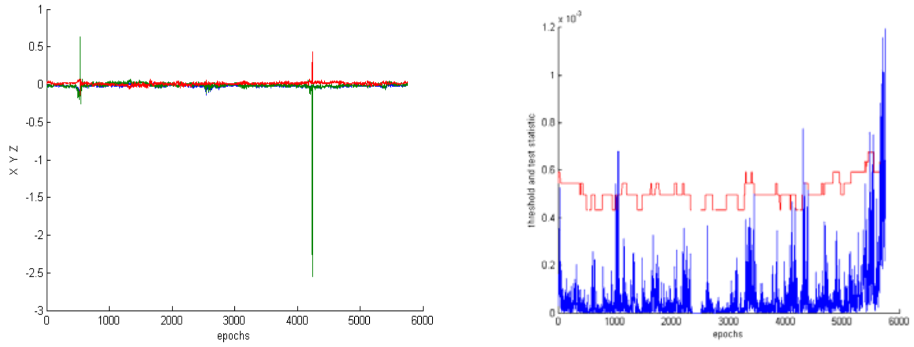


Figure 10. Illustration of Horizontal Protection Level



a b

Figure 11. Illustration of position errors removing fault satellite and the corresponding detection threshold and test statistic

Table 5. Overall Probability of False Alert and Missed Detection

	Error added	Missed Detection Probability	False Alert Probability
I	0	NAN	0.972%
II	0.25 cycles	7.61%	NAN
III	0.5 cycles	0.387%	NAN
IV	1 cycles	0	NAN
V	2.5 cycles	0	NAN
VI	a ramp error at a rate 0.01m/epoch	2.9%	NAN
VII	a ramp error at a rate 0.1m/epoch	0.0527%	NAN
VIII	0	NAN	0.74%

Conclusion

Introducing integrity monitoring techniques into RTK solutions and applications is challenging because of complexity of integer ambiguity solutions and geometric collections between measurements. This paper attempts to consider the accuracy and integrity requirements, and test the performance of the basic RAIM statistics. The required positioning parameters of precision agriculture were outlined in this paper. The modified snapshot RAIM method is proposed allowing for use of measurements from two consecutive epochs to benefit the fault detections. Based on a 24 hours baseline data set and the reference ambiguity and position solutions obtained and analysis with added artificial errors, it is clearly seen that drift errors of as small as 5 cm can be detected with 99.3 %. With the ramp error as slow as 0.1m/epoch, the probability of missed detection can be the higher than 99.9%. HPL is also given in this paper which is more precise than the traditional pseudorange RAIM algorithm. Based on this work, carrying out the experiment with real trial data is expected, and to reduce the false alert events with more visible satellites is still a challenge and of significance in the future.

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